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Review

Possible impacts of sea level rise on disease transmission and potential adaptation strategies, a review

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ABSTRACT

Sea levels are projected to rise in response to climate change, causing the intrusion of sea water into land. In flat coastal regions, this would generate an increase in shallow water covered areas with limited circulation. This scenario raises a concern about the consequences it could have on human health, specifically the possible impacts on disease transmission. In this review paper we identified three categories of diseases which are associated with water and whose transmission can be affected by sea level rise. These categories include: mosquitoborne diseases, naturalized organisms (*Vibrio* spp. and toxic algae), and fecal-oral diseases. For each disease category, we propose comprehensive adaptation strategies that would help minimize possible health risks. Finally, the City of Key West, Florida is analyzed as a case study, due to its inherent vulnerability to sea level rise. Current and projected adaptation techniques are discussed as well as the integration of additional recommendations, focused on disease transmission control. Given that sea level rise will likely continue into the future, the promotion and implementation of positive adaptation strategies is necessary to ensure community resilience.

Contents

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1. Introduction

Sea level rise is a consequence of climate change and rising global temperatures. Climate change has been positively related to human influences; therefore, its effects over sea level are unlikely to disappear in the future (IPCC, 2014; U.S. EPA, 2016; Shindell et al., 2017). In fact, sea level trends show that the mean rate of global averaged sea level rise was in the range of 1.5–1.9 mm/yr between 1901 and 2010 and in the range of 2.8–3.6 mm/yr between 1993 and 2010 (IPCC, 2014), demonstrating a rapid increase over the last decade. It is expected that sea level rise by 2100 could be even higher than predicted (between 0.26 and 0.82 m), and will continue rising after 2100 (FOCC, 2010).

Since its recognition, several studies have been executed to evaluate the impacts of sea level rise and climate change on coastal communities and to establish adaptation strategies, mainly from the point of view of future planning and infrastructure, resources and socio-economic impact (Bates et al., 2008; Bloetscher et al., 2000; FOCC, 2010; Hanson et al., 2011; SFRCC, 2015; Tebaldi et al., 2012). However, until recently the implications over public health were not fully considered (Ebi et al., 2009; Crimmins et al., 2016; Swaminathan et al., 2017; Veenema et al., 2017), and few practical adaptation strategies focused on health risk prevention have been developed (Bloetscher et al., 2016; Boguszewski, 2015; Craig, 2010; FIHI, 2016; FPHI, 2014; Ramasamy and Surendran, 2011; Ramasamy and Surendran, 2012; SFRCC, 2015). Therefore, the objectives of this manuscript are to describe possible changes in the transmission of water-related diseases in response to sea level rise in coastal communities, as well as to describe potential engineering solutions to mitigate the transmission of these diseases. Diseases considered are those associated with water: those associated with standing water and subsequent mosquito breeding, and those transmitted through water contact, inhalation, or ingestion of water or consumption of contaminated fish/shellfish. As a critical case of the need to prepare for potential changes in disease transmission, the City of Key West, Florida, a case study site, is used to exemplify some of the adaptation strategies.

To address these objectives this study includes a literature review on sea level rise and water-related diseases. The literature is also reviewed for general strategies to reduce disease transmission with an emphasis on evaluating the influence of salinity, given that the focus is on coastal communities. Sea level rise data were collected from sources such as: the Florida Oceans and Coastal Council (FOCC), the Intergovernmental Panel on Climate Change (IPCC), the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Army Corps of Engineers (USACE). This data was compared and analyzed to evaluate past, current and future trends of sea level in South Florida. Technical reports and papers published by the Centers for Disease Control and Prevention (CDC), the World Health Organization (WHO), the Florida Institute of Health and Innovation (FIHI), the Florida Department of Health (FDOH), the U.S. Environmental Protection Agency (U.S. EPA), and the Pan American Health Organization (PAHO) were reviewed and analyzed to obtain data regarding the selected water related diseases, including: transmission route, infection cases statistics and vulnerability to changes in water salinity patterns.

Some of the descriptive examples that focus on the case study site of Key West were inspired through a workshop entitled, "Review of the Florida Resilient Redesign II Proposal for the case of study (City of Key West)," which was organized by the Florida Climate Institute to address the needs of the Southeast Florida Regional Climate Change Compact (SFRCC). The goal of the workshop was to "identify the physical and planning adaptations necessary to reduce the risk and potential for disruptions, damage and economic losses associated with climate change and to develop transferable models relevant to development and redevelopment opportunities throughout the region". The purpose of the SFRCC is to "coordinate mitigation and adaptation activities across county lines." The compact was signed on behalf of four southeastern counties in Florida, USA which from north to south include Palm Beach, Broward, Miami-Dade and Monroe. Key West is the southernmost city located in the southernmost county, Monroe County. This city is considered by many to already experience impacts from sea level rise. The Key West working group for this meeting consisted of experts who spent two days visiting field sites and designing potential adaptation strategies for Key West, with the objective to design an urban-coastal community that is resilient and able to adapt to: sea level rise of a minimum of 60 cm by 2060, tidal flooding, extreme rainfall and storms, increased storm surge, water supply constraints, increase in temperature, heat waves, among others. The list of participants in the working group is included in the supplemental text. This manuscript includes a summary of the Key West working group findings along with additional recommendations.

2. Sea level rise review

Sea level rise has become a matter of increasing global concern in the last three decades. In fact, sea levels have been rising constantly over the past century with a global mean rate on the order of 1 mm/year (Gregory, 2013). It is expected that over the next 15–30 years, the effects of sea level rise would become even more noticeable, with continually increasing rates of rise, especially along the United States East and Gulf Coasts (Spanger-Siegfried et al., 2014; U.S. EPA, 2016), as well as in Southeast Asia, Oceania and Eastern South American coasts (IPCC, 2014).

In the last decades, the trend has increased dramatically, at a rate more than 50% higher than the historic global mean value of 1 mm/year during the 20th century. In particular, over the last 20 years the rate of increase is 300% over the prior rate, at around 3.2 mm/y for global mean sea level rise (IPCC, 2014). Much of the available data supports evidence that the rate of sea level rise is likely to increase in the upcoming decades, while no evidence currently proves that it could possibly have a steadying or even decreasing future trend (Bloetscher et al., 2016; FOCC, 2010; Gregory, 2013; IPCC, 2014).

Sea level rise is related to climate change, which has been caused by global warming (IPCC, 2014). Global warming has its roots in industrial development, with the massive release of CO_2 during the industrial revolution and beyond, ultimately allowing the greenhouse effect to take place. This is directly related to industrial development, making it unlikely for the rate of sea level rise to decrease in the near future (Gregory, 2013). The IPCC has developed a sequence of scenarios for global warming depending upon the amount of CO_2 emitted to the atmosphere as a result of stringent mitigation efforts versus a high emission scenario. Given this range of scenarios the IPCC predicts increases in mean global temperature to vary between 1.0 and 3.7 °C by the end of the century. Consequently, sea level is anticipated to rise due to three main causes: warming of the ocean (thermal expansion), loss of glaciers (increased water volume in the sea), and reduction of liquid water storage capacity on land (IPCC, 2014). On a global average, the sea level is anticipated to increase between 0.40 and 0.63 m by 2100.

In South Florida, an analysis of measured sea level data indicates clear trends of sea level rise. For example, the analysis shows an average rate of increase of 4.62 mm/yr at the Virginia Key (Miami) tide station located along the Atlantic shore of south Miami-Dade County, 3.96 mm/yr at the Lake Worth Pier tide station (north end of Palm Beach County), and 2.40 mm/yr at the City of Key West

tide station. In particular, the City of Key West, has recorded sea level data since 1922. From this data it is possible to observe the obvious upward trend in sea level over the recorded period (Fig. 1a). In addition, comparing the data for the last 15 years (Fig. 1b), it can be noted that in this period the rate of increase has become more pronounced (6.6 mm/yr), approaching the high level predictions from the National Oceanographic and Atmospheric Administration (NOAA) and U.S. Army Corps of Engineers (USACE). Furthermore, the recorded data show that the rates of increase for Virginia Key and Lake Worth Pier have experienced similar outcomes over the last 15 years, resulting in rates of 7.2 mm/yr and 15.7 mm/yr, respectively.

South Florida is of special interest when considering the possible impacts of continuing sea level rise, since it is considered one of the world's most vulnerable areas (Bloetscher et al., 2016). It is believed that in this region sea level rise will probably become higher than the global average, due to predicted changes in ocean currents such as the Gulf Stream which, runs along the Atlantic coastline of eastern Florida (SFRCC, 2015). In addition, saltwater intrusion into the Biscayne Aquifer, the main source of freshwater for Miami-Dade County residents, would impair the water supply and surface soils (FIHI, 2016). For example, studies have shown that a net 18 square kilometers of freshwater resources were lost from the Biscayne Aquifer since 1995 (Prinos et al., 2014), presumably associated with changes in climate, particularly increased sea levels and saltwater intrusion. In addition, it has been demonstrated that climate driven seawater intrusion and salinization of coastal environments can affect their biochemistry and promote the release of contaminants retained in the soil (LeMonte et al., 2017). Moreover, both Miami-Dade County and the City of Key West have experienced an increase in the frequency of flooding and stress to the storm water management systems (Spanger-Siegfried et al., 2014). Buildings in these communities were previously built at least 1 m above the actual sea level, as a preventive measure from flooding problems. However, using 5 year moving averages current sea level rise in the area is already over one-tenth of a meter as observed from the Key West station period of record (1922–2016). Furthermore, current predictions indicate an increase in sea levels of around another half a meter by the end of 2060 (Rahmstorf, 2006; U.S. EPA, 2015; Gregory, 2013), further decreasing the safety margin of most buildings to just 40 cm.

3. Identified diseases

Although there are many diseases associated with water, the focus of this study includes three categories of disease (mosquito-borne diseases, naturalized organisms and fecal oral diseases) and those with the largest prevalence rates between the latitudes of 26°58′ N to 20°59′ N. These latitudes were chosen to represent the latitudes for the counties in the SFRCC, which range from 26°58′ N

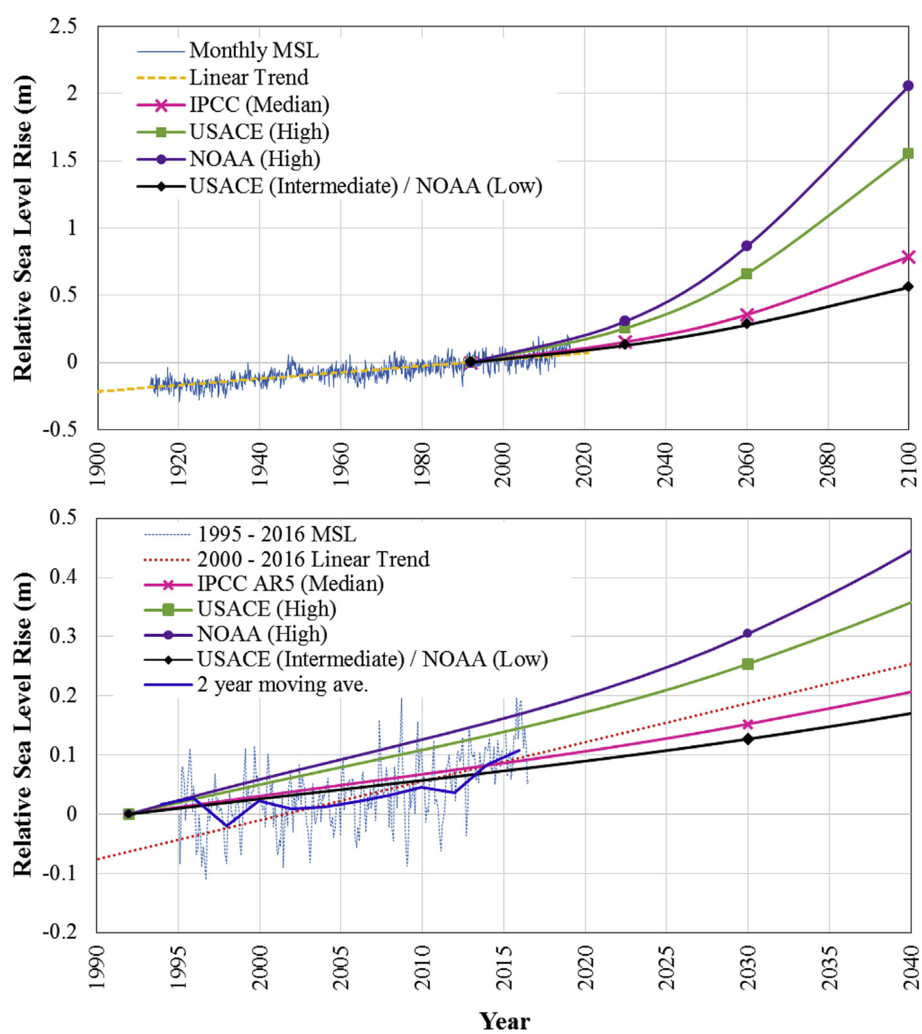

Fig. 1. Sea level data and predictions for the City of Key West, Florida. A. Period: 1913–2016. B. Period: 1995–2016.

in northern Palm Beach County to 24°33′ N at Key West. The study range was further extended, assuming a temperature increase of 3 °C; which is consistent with forecasts for global temperature warming by the turn of the century (IPCC, 2014), assuming a scenario with low-end anthropogenic reductions in CO_2 emissions. The decrease in temperature associated with latitude in the northern hemisphere is 0.86 °C per latitude degree (Gates et al., 1999), resulting in an equivalent latitude reduction by 3° and 29 s to set the southern extent to 20° 59' N.

3.1. Mosquitoborne diseases

Vector borne diseases are caused by pathogens transmitted to humans through a vector (mosquitoes, ticks, flies, among others). The seasonal and geographic distributions of vector borne diseases will likely be altered as a result of climate change (Beard et al., 2016). Mosquitoborne diseases are of particular interest, since the expansion of shallow stagnant water sets an ideal scenario for mosquito reproduction and propagation (Craig, 2010). The majority of mosquitoborne diseases are arboviruses. A notable exception is malaria, with a parasitic protozoan as the primary infectious agent (WHO, 2016). This paper includes a discussion of the most notable arboviruses and also malaria.

The most common arboviruses detected in the United States cause encephalitis, an inflammation of the brain tissues. In most cases arboviral encephalitis infections in humans are mostly asymptomatic or generate flu like symptoms, with fever, headaches, muscular pain and weakness. Only a small proportion of human infections progress to develop encephalitis. As these infections are caused by viruses, antibiotics are not an effective treatment for humans. Currently, vaccines for the encephalitis illnesses mentioned are very limited and in the experimental stages (FDOH, 2014). The first approved arbovirus vaccine specifically for dengue fever was permitted for use in six countries during 2017. It consists of a live attenuated virus that promotes host immunity to the virus. However, its effectiveness depends on the age of the vaccinated group and local transmission intensity (Ferguson et al., 2016).

Among arboviruses that cause encephalitis, St. Louis Encephalitis virus (SLEV), Eastern Equine Encephalitis virus (EEEV), La Crosse Encephalitis Virus (LACV) and West Nile virus (WNV) are most frequently detected (CDC, 2015a). In particular, WNV represents the most recurrent arboviral illness in the United States, with 2469 reported cases nationwide as of the year 2013 (Lindsey et al., 2014).

Other important arboviruses to be considered are dengue fever, Chikungunya, Zika and yellow fever viruses, which are transmitted by *Aedes aegypti*. Although at the moment dengue does not pose a major public health threat in the US, it represents a major concern worldwide within the target latitudes, with 390 million cases reported as of 2010 (CDC, 2017a). In 2013 a dengue outbreak affected the Americas and the Caribbean, including Puerto Rico and the Virgin Islands, resulting in 837 cases reported in US territories (CDC, 2015a). In 2009–2010 Key West suffered its worst outbreak, with 22 cases reported (Radke et al., 2009). In contrast to viruses like SLEV, EEEV and WNV, for which humans do not serve as a reservoir of infection for mosquitos, dengue virus has humans as its main reservoir from which mosquitos can become infected (FDOH, 2014). Therefore, tourist destinations could be more susceptible to dengue. At tourist destinations visitors from endemic countries can carry the virus to these areas and serve as the reservoir for additional disease transmission via mosquitos. As a result uninfected tourists and local residents at these locations can become infected thereby propagating local transmission and transmission within the home countries of the tourists upon their return.

Similarly, Chikungunya virus is not considered a major public concern through local transmission in the continental US. In 2016, 248 travel-associated cases (where the virus transmission occurred in endemic countries and the infected person traveled back to the US) were documented in 38 states, most of them in California and New York (CDC, 2017c). Locally acquired infections (where virus transmission occurs through the bite of infected mosquitos within that location) are reported within the US territories (Puerto Rico and the Virgin Islands), with a total of 180 cases, 99% of them in Puerto Rico (CDC, 2017c). An outbreak began in 2013 within central and south America; since then more than 1.7 million suspected cases have been reported. In 2017 only, over 122 thousand confirmed cases within 17 countries were reported by the Pan American Health Organization (PAHO, 2017a).

Yellow fever, on the other hand, is rarely detected in the US. Nevertheless, some countries in the Caribbean and South America within the target latitudes are considered endemic areas or have high risk of transmission. The disease has been well controlled through mass vaccination campaigns, especially in Africa, where no outbreaks were detected during 2015, within the target latitudes identified through this paper. Outside the latitudes, however, yellow fever transmission continues with three countries in South America reporting circulating yellow fever virus in 2017 (PAHO, 2017b) and an on-going 2016 outbreak in Southern Africa which ended February 2017 (WHO, 2017a).

At the beginning of 2016, Zika virus was declared by the World Health Organization a Public Health Emergency of International Concern, as a result of Brazil's outbreak that began during May 2015. Although a mosquitoborne disease, the virus is also transmitted through sexual routes, and has been known to cause birth defects (microcephaly) when pregnant women are infected. As of February 2017, 2654 cases of microcephaly have been reported worldwide (WHO, 2017b). In the United States, 935 cases of Zika virus infection have been reported, all of them travel-associated (CDC, 2017b). However, local mosquitoborne transmission of the virus in the U.S. was first confirmed by the CDC at the beginning of August 2016, with 216 cases in Florida as of April 2017 and one additional locally transmission case in Florida as of November 2017. More intense spread has been documented in the US territories, with almost 37,000 locally acquired mosquitoborne infections (CDC, 2017b).

Malaria is of concern in a worldwide scenario, and is currently transmitted within the latitudes selected for this paper. In 2015, the WHO estimated a total of 212 million cases, of which the majority occurred in the African region (90%), followed by the South East of Asia (7%). The infections in the Americas represented 0.3%. A total of 429 thousand deaths were also reported for this disease for the same year (WHO, 2016). However, efforts to control the disease transmission have been able to reduce the number of cases present in comparison with the year 2000; with a global reduction of 14% in the total number of infections and 52% in the number of deaths (WHO, 2016). Treatment methods reported by the WHO have included medically based methods, such as artemisinin based combination therapy, plus environmental based methods, such as use of insecticide-treated mosquito nets and indoor residual spraying.

3.2. Naturalized organisms

Naturalized organisms are those that thrive in seawater and in contaminated fresh waters. These organisms include the Vibrio bacteria and toxic algae. Of the Vibrio species, the most common to cause infection are: *Vibrio vulnificus*, *Vibrio parahaemolyticus* and *Vibrio cholerae* (CDC, 2015b). *V. vulnificus* and *V. parahaemolyticus* cause an infection called vibriosis, which can manifest mild to

severe gastroenteritis, primary sepsis, or skin and soft tissue infection, depending on the transmission route (Newton et al., 2012). The infection is mainly contracted by the ingestion of raw shellfish (especially oysters) or by exposing open wounds to brackish or sea water. In contrast, *V. cholerae* causes an infection known as cholera, which is characterized by a life threatening acute watery diarrhea. However, the infection is easily treated. Most of the cases are caused by ingestion of water or food contaminated with human fecal matter (Newton et al., 2012). Similar to *V. vulnificus* and *V. parahaemolyticus*, *V. cholerae* can also be transmitted by eating raw shellfish harvested from contaminated waters.

The expansion of areas covered with shallow waters could also implicate a geographical extension of the incidence area of toxic algae blooms and exposure of new populations (Craig, 2010; Trtanj et al., 2016; Buratti et al., 2017). Toxic algae blooms are characterized by a rapid increase of the toxin producing algae, caused by changes in water quality such as: temperature, nutrients and light. Common toxic algae blooms in the United States are caused by cyanobacteria and Florida red tide blooms (*Karenia brevis*) (FDOH, 2017).

Toxins produced by some algae can be harmful for humans and animals that drink or are in contact with contaminated waters. In the case of cyanobacteria, the toxins are believed to accumulate in fish and shellfish. High concentrations of the toxins can affect the gastrointestinal tract, nervous system and skin. In the case of Florida red tide, the algae produce a suite of natural toxins called brevetoxins (Fleming et al., 2011). The most common human health manifestation is gastrointestinal illness due to the consumption of contaminated seafood (Kirkpatrick et al., 2010) and respiratory irritation caused by inhalation of toxins mixed with sea spray produced when waves break at the shore (Kirkpatrick et al., 2011). During times of red tides, it is advised not to ingest shellfish like clams, shrimps, lobster and oysters harvested from waters with red tides, since shellfish (as filter feeders) can concentrate toxins (FDOH, 2017). People with underlying respiratory susceptibilities (e.g., uncontrolled asthma) should avoid the beaches during times of active nearshore blooms (Bean et al., 2011).

3.3. Fecal-oral diseases

In a sea level rise scenario, the intrusion of seawater could cause disturbances to sewer systems (by flooding the collection lines). Therefore, it is also important to consider the diseases that are typically transmitted by exposure to contaminated waters, especially those pathogens that follow a fecal-oral route. According to the Centers for Disease Control and Prevention (CDC), the most frequent fecal-oral pathogens associated with outbreaks in the United States are: *Campylobacter jejuni* (bacteria), *Giardia intestinalis* (protozoa) *Cryptosporidium* sp. (protozoa), *Shigella* (bacteria), *Escherichia coli* O157:H7 and O111 (bacteria) and enteric viruses (CDC, 2015b). Of particular significance is the transmission of protozoal illnesses for which common disinfection systems, via chlorination, are not effective; failing to inactivate the protozoal microbes. Furthermore, *Legionella* sp. is the waterborne pathogen with the highest incidence in the United States (CDC, 2015b). However, *Legionella* is not transmitted via fecal-oral routes. It is transmitted by the inhalation of contaminated aerosols. Its natural reservoir consists of warm fresh water (WHO, 2007) with outbreaks typically associated with improperly treated municipal water in residential settings, and the inhalation of aerosols from cooling towers. Although *Legionella* is typically found in freshwaters, several studies have demonstrated that the bacteria can survive in marine environments (Heller et al., 1997; Gast et al., 2011). The ability to tolerate salty water thereby raises concerns over disease transmission of *Legionella* species in coastal environments, especially in situations that promote the formation of aerosols from contaminated waters.

4. Disease mitigation

4.1. Mitigation of mosquitoborne diseases

The life cycle of a mosquito includes a larval stage that requires stagnant water, and an adult-female blood feeding stage required for the development of eggs in the female after mating. The time it takes for a blood feeding female to develop from an egg is variable and dependent on several factors including mosquito species, larval density and availability of resources. For *Aedes aegypti* development occurs over a period of about 10 days but can be shorter in areas of high humidity and warmer temperatures (da Cruz Ferreira et al., 2017). Mitigation of mosquitoborne diseases will require interruption of the - life cycle (Fig. 2). These mitigation strategies can be separated into mechanical, biological, and chemical controls.

With respect to temperature, for the United States, most cases of mosquitoborne diseases occur during the warmer months (June–September), when the vector is more active. However, in some states like Florida, the incidence can be observed even during winter months, due to warmer temperatures in the region. In fact, climate change not only contributes to a higher exposure of mosquitoborne diseases by spreading the areas of mosquito reproduction, it also causes the expansion of the mosquito active season by the increasing the number of warm temperature months (Craig, 2010). To further increase mosquito reproduction, some mosquito species, which are traditionally considered to be fresh water mosquitos, have adapted to reproduce within brackish water environments after events of sea water intrusion (Ramasamy and Surendran, 2011, 2012). The case of *Aedes aegypti* is of particular concern since it is the vector responsible for transmitting dengue, Chicungunya, Yellow Fever and Zika viruses. Table 1 summarizes the most relevant mosquito species for the latitudes selected, along with their related diseases and the optimal salinity and temperature ranges for their reproduction and survival. Overall, the species considered in this paper are capable of thriving in brackish water (salinity between 5 and 30 ppt.) with *Culex* and *Aedes* spp. associated with fresh and brackish waters and *Anopholes* spp. capable of reproducing under high (39 ppt) salinity conditions. *Aedes* spp. has the widest temperature range (17–34 °C) with optimal temperatures for the latitudes selected. Therefore, sea level rise and the intrusion of warm sea water will likely contribute to the establishment of ideal conditions for mosquito reproduction and the propagation of mosquitoborne diseases.

There are three categories of mitigation for mosquitoborne diseases. The first type of mitigation strategy involves mechanical control methods. Mechanical methods are focused on preventing water stagnation to minimize the availability of mosquito reproduction sites. It is anticipated that water stagnation will increase with sea level rise. This is because waters along coastlines tend to be shallow due to relatively flat bottom slopes associated with the flat terrestrial topography. Sea level rise will result in a horizontal extension of shallow waters inland due to the flat topography of the area, thereby increasing the spatial extent of flat shallow waters towards more populated areas. One critically important method to reduce the mosquito population is to prevent the accumulation of water, at both large and small scales. On the large scale standing water can be avoided by draining and/or pumping of shallow surface water ponds, surface grading, subsoil drainage, deepening of shallow areas, and hydraulic filling, among others (Salvato, 1992). At the smaller individual property owner scale, measures include: elimination of standing water from barrels, empty cans, tires,

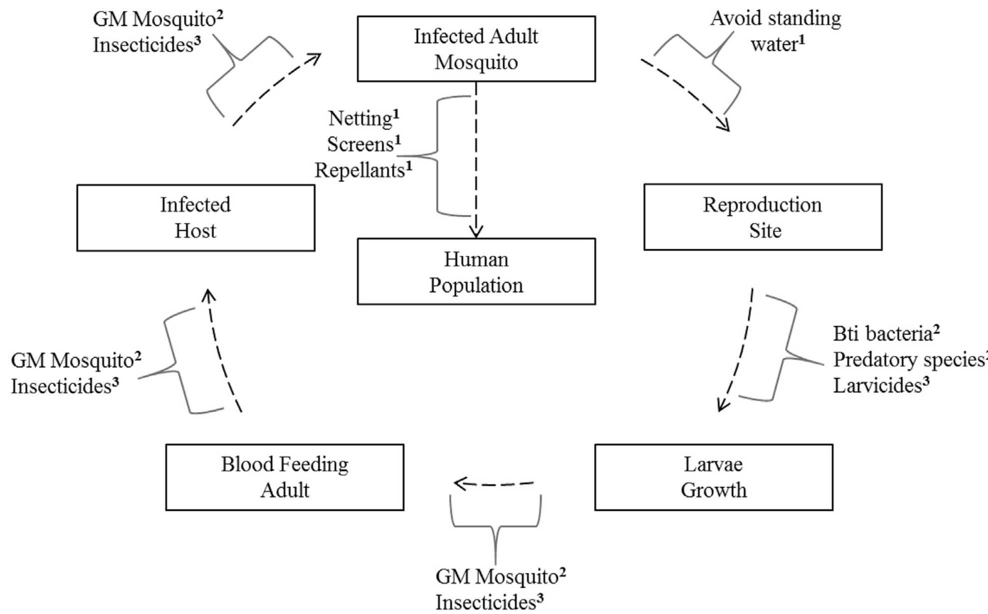

Fig. 2. Mitigation of mosquito-borne diseases. Mitigation can be grouped into three broad categories: 1 - mechanical methods, 2 – biological methods, 3 – chemical methods. Superscripts shown for various mitigation strategies correspond to one of the listed categories.

gutters, boats, garbage containers, unused swimming pools, proper disposal of used containers and tires to avoid undesired water collection, keeping swimming pools and hot tubs in proper functioning conditions, continuously changing water in flower pots, pet bowls and bird baths (every three to four days), cleaning roof gutters and draining flat roofs, covering with a screen or lid any rainwater collection barrel or cisterns, repairing broken windows or door screens, and the installation of mosquito traps, among others (Connelly et al., 2014). Also, new South Florida building codes are proposed that would allow the use of water cisterns to collect rainwater; which could help minimize the quantity of storm water runoff and potential water stagnation caused by excess storm water runoff. However, these cisterns should be kept properly covered, to avoid becoming new breeding sites.

The second category of mitigation strategies, biological methods, focuses on using biological or ecological means of controlling mosquito proliferation, which can be more desirable to reduce mosquito populations and mitigate arboviral disease transmission, due to their eco-friendly nature (Bonelli et al., 2016). Biological methods are based on non-chemical (larvicides) alternatives that interrupt the life cycle of the mosquito, with minimum environmental impact. These can be achieved by the introduction of organisms that prey on or compete with target species. In the case of mosquito control, predatory fish and copepods have been shown to be successful (WHO, 2017c) in reducing the mosquito population. When introducing predatory fish to the mosquito source site, it is important to select native species which would prevent threats to the indigenous fauna (WHO, 2017c). Many fish species native to Florida can be potentially used for larvae control (Connelly et al., 2014). Each of the fish requires optimal temperature and salinities for their survival (Table 1). Predatory copepods, small crustaceans naturally found in fresh and brackish waters, can also feed on early stage larvae. These crustaceans can be used in stagnant water that is not intended to be drained. As well as in the case of fish, it is important to introduce native copepods. Therefore, these should be collected from local source waters and then introduced into the mosquito reservoir (Connelly et al., 2014). In some cases, reintroduction of copepods is necessary until their populations are sustainable (WHO, 2017c).

Another form of biological and ecological mitigation is the application of *Bacillus thuringiensis israelensis* (Bti), a naturally occurring soil bacteria that is believed to generally have minimal impacts on non-target organisms (Salvato, 1992). Bti, which is effective in controlling several mosquito species (*Aedes* and *Culex*), produces toxic proteins that are ingested by the larvae, causing disruption of cell membranes and subsequently death of the organism (Boyce et al., 2013). Although most of the toxins produced by Bti are non-toxic to humans, studies have shown some strains may release beta-exotoxins shown to be toxic to mammalian cells (Gonzalez Rizo et al., 2016); caution is needed in selecting Bti strains that minimize unintended impacts.

Additionally, the application of novel techniques has been gaining interest amongst the authorities responsible for mosquito control. These techniques include the introduction of genetically modified (GM) mosquitos to control their population. The method is based on modifying the genome of the organisms to control a specific trait, which is then passed down to its descendants. In mosquitoborne disease mitigation, genetic engineering can be used to prevent disease transmission, by either altering mosquito philology (so the disease-causing virus or protozoa cannot survive) or by reducing the population through sterility (making the male sterile or causing the death of the descendants). Genetically modified (GM) mosquitos have been used to reduce populations with success in several countries, achieving a high rate of reduction of *Aedes aegypti* populations (Connelly et al., 2014). For example, a field trial (23-week period) executed in the Cayman Islands in 2010 successfully introduced genetically modified males that were able to reproduce with wild females, resulting in an 80% population reduction (Harris et al., 2012). The same types of genetically modified males were evaluated in Brazil, with a 95% reduction of the mosquito adult population in a year (Carvalho et al., 2015). However, over time there has been opposition regarding the effectiveness of these trials in Brazil due to questions about its long term efficacy and opposition to the release of genetically modified mosquitos (FKEC, 2017). An alternative to this approach is the use of *Wolbachia* strains (a naturally occurring parasitic bacteria that can self-sustain in mosquito populations) as a biocontrol. This technique reduces adult lifespans and interferes

Table 1
Mosquito and predatory fish species in terms of salinity and temperature ranges.

Vector					
Mosquito species	Related Diseases	Salinity (ppt)	Temp. (°C)	Notes	References
Culex spp	West Nile Virus Arboviral Encephalitis	*Culex tarsalis*: 0–25 *Culex sitiens*: 0–20	18–30	*Culex tarsalis* is the most common *Culex* spp mosquito in the US. Responsible for most of the WNV transmissions	(Ramasamy and Surendran, 2011, 2012), (Patrick and Bradley, 2000), (Dohm et al., 2002)
Aedes Aegypti	Dengue Zika Chicungunya Yellow Fever	0–15 0–9	12–34	Naturally a freshwater mosquito. However, it has been observed to adapt to brackish waters in sea water intrusion scenarios	(Ramasamy and Surendran, 2011), (Clark et al., 2004) (Jude et al., 2012) (Mullenbach et al., 2005), (Liu-Helmersson et al., 2014)
Anopheles spp	Malaria	2–39	17–33		(Jude et al., 2012) (Beck-Johnson et al., 2013)
Mitigation					
Predatory Fish Species		Salinity (ppt)	Temp. (°C)	Habitat	References
Eastern Mosquitofish (*Gambusia holbrooki*)		0.5–35	0–35	Native to US Gulf and Atlantic coasts. Survives in waters with low oxygen concentration. Can be found in fresh, brackish waters and salt marshes	(Gall et al., 1980)
Eastern Mudminnow (*Umbra pygmaea*)		0–0.5	1–20	Ponds, lakes, ditches and creeks	(Kern, 2002), (Verreycken et al., 2010)
Pygmy Killifish (*Leptolucania ommata*)		0–0.5	18–27	Ponds, lakes, ditches and creeks	(Kern, 2002)
Lined Topminnow (*Fundulus lineolatus*)		0–0.5	18–24	Ponds, lakes, ditches and creeks	(Kern, 2002)
Golden Topminnow (*Fundulus chrysotus*)		0–20	18–25	Coastal Rivers in the Gulf of Mexico. Atlantic coast, from South Carolina to Florida. Requires slow current flows. Primarily freshwater fish	(Ross and Brenneman, 1991)
Sailfin Molly (*Poecilia latipinna*)		0–70	20–28	Native to US Gulf and Atlantic coasts, found in fresh and brackish waters. Absent from turbulent waters	(Nordlie et al., 1992)
Least Killifish (Heterandria formosa)		0–12	20–26	Native to US Gulf and Atlantic coasts, found in fresh and brackish waters	(Martin et al., 2009)
Banded Pygmy Sunfish (*Elassoma zonatum*)		0–0.5	5–32	Native to US Gulf and Atlantic coastal plain, found in low gradient streams, with marshy environments	(Mettee, 2008)
Everglades Pygmy Sunfish (*Elassoma evergladei*)		0–0.5	5–32	Native to swampy areas of Florida and Georgia, fresh water fish	(Page and Burr, 2011)
Bluespotted Sunfish (*Enneacanthus gloriosus*)		0–0.5	5–32	Native to US Gulf and Atlantic coastal plain, found in low gradient streams, with marshy environments	(Murdy and Musick, 2013)
Flier (*Centrarchus macropterus*)		0–0.5	12–22	Native to US Gulf and Atlantic coastal plain and Mississippi, found in freshwater drainages and swamps	(Page and Burr, 1991)
Spotted Sunfish/Stumpknocker (*Lepomis punctatus*)		0–0.5	20–24	Native to US Gulf and Atlantic coastal plain, found in shallow ponds, creeks and lakes with heavily vegetated environments	(Page and Burr, 1991), (Hill and Cichra, 2005)
Bluegill or Bream (*Lepomis macrochirus*)		0–0.5	1–36	Native to the Great Lakes and Mississippi River basin, found in lakes and ponds with slow currents	(Page and Burr, 1991), (Beitinger and Bennett, 2000)
Redear Sunfish or Shellcracker (*Lepomis microlophus*)		0–0.5	20–31	Native to US Gulf and Atlantic coastal plain, found in low gradient streams and small rivers, found in clear warm waters	(Page and Burr, 1991)

with fertility and pathogen replication (Iturbe-Ormaetxe et al., 2011; Suh et al., 2017).

Chemical methods (larvicides and insecticides), the third method of mitigation, are applied to control larvae and adult mosquito populations. There are several U.S. EPA approved chemicals that can be used as larvicides, and can be applied in liquid form (spraying) or as pellets or tablets. Larvicides can be classified as insect growth inhibitors, organophosphates, or oil films. Insect growth inhibitors (S-Hydroprene, S-Kinoprene, Methoprene and S-Methoprene) prevent larvae from developing into adult mosquitoes, by interfering with growth hormones (U.S. EPA, 2001). Organophosphates affect the nervous system of the larvae, inhibiting growth. Oil films control mosquitos through a physical process. They are applied as thin layers over the water surface and restrict oxygen access, causing larvae to drown (U.S. EPA, 2017). Adult mosquito control with insecticides is achieved by spraying affected areas with U.S. EPA approved chemicals, such as: malathion, naled (organophosphates), prallethrin, etofenprox, pyrethrins, permethrin, resmethrin and sumithrin (synthetic pyrethroid) (U.S. EPA, 2017).

Chemical controls should only be considered when mechanical and biological control methods have not been effective or are not possible to use. The use of chemical methods should be limited as this mitigation strategy is known to result in the development of resistant mosquitos (Salvato, 1992). Resistance is believed to be caused by mutations that lead to higher metabolic detoxification and lower sensitivity of the target proteins (Liu, 2015). Repeated applications of pesticides result in the survival of mosquitos with such mutations thereby creating a new population with the mutations suitable for survival. In practice, the development of

insecticide resistance has been linked to recent arboviral disease outbreaks, as in the case of Chicungunya fever in the Republic of Congo (Kelvin, 2011). Moreover, the WHO has identified a threat on the effectiveness of malaria control methods due to the development of chemical resistance to insecticides, particularly to pyrethroid. Sixty of 78 countries surveyed had reported resistance to at least one type of insecticide (WHO, 2016).

To successfully achieve proper domestic prevention, it is important that the community is continuously informed about available mitigation techniques, including eliminating standing water from their property and utilization of long sleeve clothing and insect repellants to minimize the probability of a mosquito bite. Therefore, comprehensive information campaigns should be included as part of an integrated strategy to minimize mosquito-borne disease propagation.

4.2. Mitigation of naturalized microorganisms

As in the case of vector borne diseases, sea level rise can increase the geographical expansion of the incidence area, exposing new populations to harmful microorganisms naturally found in water, the *Vibrios* and harmful algae. Warmer water bodies, due to climate change and changing levels of coastal nutrients (nitrogen and phosphorous), will likely play an important role in the persistence of naturalized microbes. In addition, *Vibrio* proliferation is sensitive to salinity, whereas growth of toxic algae is dependent upon solar radiation (Fig. 3). Therefore, designing a proper monitoring system to detect or predict the presence of harmful microbes found naturally in water (based on critical environmental factors), should be considered as part of the plans to adapt to sea level rise, especially when temperatures, salinity (Table 2) and nutrients are at the optimal range.

For *Vibrio*, the optimum temperature for growth is between 15 and 30 °C (Craig, 2010). In fact, changes in *V. vulnificus* abundance and a consequent increasing trend in the number of infection cases around the world, have been mostly attributed to climate change (Deeb, 2013; Newton et al., 2012; Randa et al., 2004; Vezzulli et al., 2012; Semenza et al., 2017). This increase has been specifically accredited to increasing water temperatures which has expanded the active season and geographical range of *Vibrios*. In the case of toxic algae, optimum temperature for algal growth is in the 20 to 35 °C range for cyanobacteria (Konopka and Brock, 1978) and 15 to 30 °C for *Karenia brevis* (Magaña and Villareal, 2006) (Table 2), and changes in surface temperature could also be linked with more frequent and intense harmful algae blooms (Moore et al., 2008). For example, the average mean temperature in Key West (25.5 °C, 1948 to 2015 period of record, Key West International Airport, National Climatic Data Center) is within the optimum range for growth of *Vibrios* and harmful algae. A 3 °C increase in ambient temperature would push the mean temperature in Key West more towards the center of the optimum range for algae growth and towards the higher end for cyanobacterial growth. Increases in atmospheric temperature due to global warming will likely increase the period and intensity of naturalized-microbe growth and persistence in tropical and subtropical climates with changing dynamics between types and species of naturalized organisms that dominate the microbial ecosystems.

Along with climate change, certain types of liquid discharges to coastal environments could contribute to localized rise of seawater temperature and changes in salinity patterns. Examples of high temperature discharges that can be exacerbated with global warming are: industrial effluents (especially warm purge from cooling towers), irregular septic and wastewater pipes leakage, power plants cooling system outfalls, and storm water runoff. Of these, discharges of power plant cooling blowdown are highly relevant for their major environmental impacts, related to the high volumes disposed and warm temperatures (up to 48 °C, which must be cooled down to at least 30 °C during the warmer months prior to discharge) (Delgado and Herzog, 2012; Fleischli and Hayat, 2014). Therefore, efforts should be made to decrease the volume of water discharged; for example, using reclaimed water in closed loops as part of the power plant cooling systems (Veil, 2007), and to reduce thermal pollution to water bodies, by implementing less

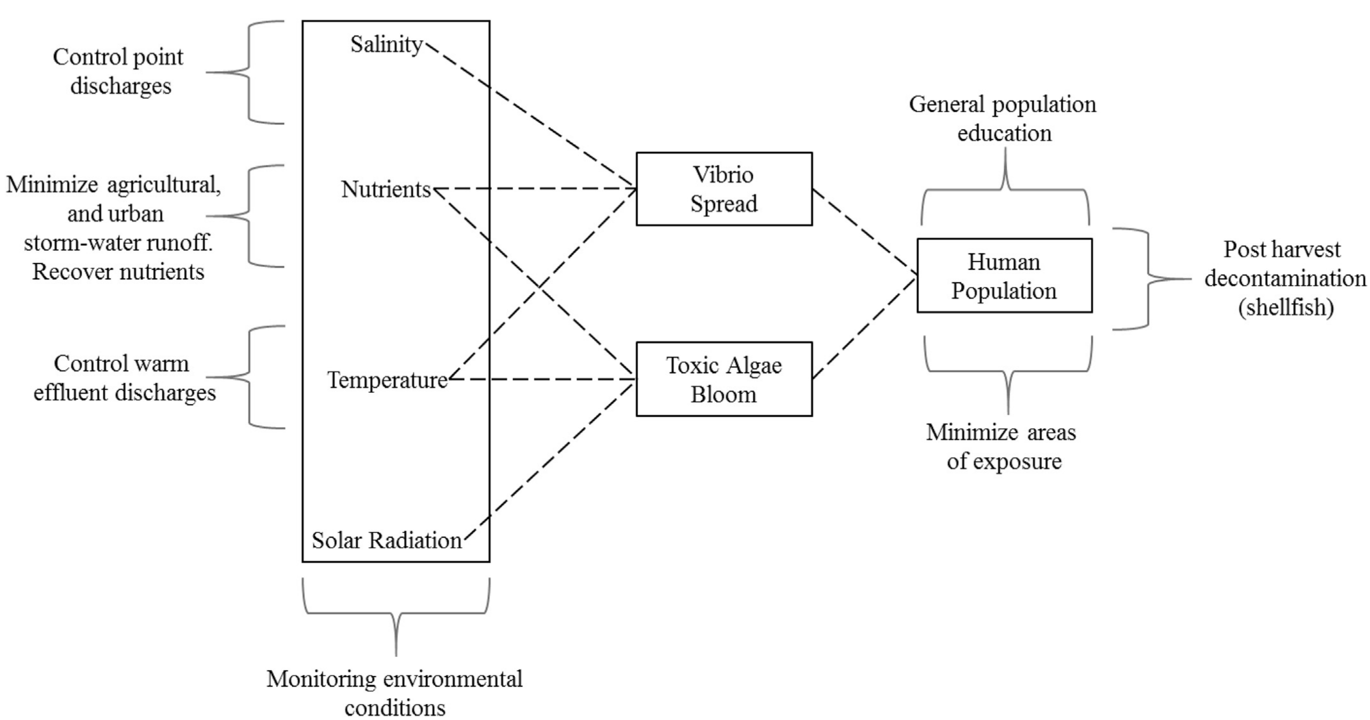

Fig. 3. Mitigation of *Vibrio* and toxic algae blooms.

Table 2
Waterborne and fecal-oral pathogens and toxic algae.

Pathogen	Related Diseases	Salinity (ppt)	Temp. (°C)	Notes	References
Vibrio sp	Vibriosis Cholera	5–25	15–30	V. spp naturally thrive in warm waters with moderate salinity	(Deeb, 2013), (Randa et al., 2004)
Legionella sp	Legionnaire's Disease Pontiac fever	0–0.5	25–42	Natural habitat fresh standing water	(WHO, 2007)
Campylobacter jejuni	Campylobacteriosis	0–0.5	30–45	Unable to grow outside host	(Garénaux et al., 2008)
Giardia intestinalis	Giardiasis	0–5	7–28		(deRegnier et al., 1989), (Kumar et al., 2016)
Cryptosporidium sp	Cryptosporidiosis	0–5	1–37	Pathogen related to most of the recreational water infections in the US	(Kumar et al., 2016) (CDC, 2015b)
Shigella	Shigellosis	0–20	4–37		(Islam et al., 1996)
E. coli O157:H7	Bloody diarrhea	0–34	4–37		(Williams et al., 2007), (van Elsas et al., 2011)
Enteric viruses	Ocular and respiratory infections Gastroenteritis Hepatitis Myocarditis Aseptic meningitis	0-30 or higher	4–30		(Fong and Lipp, 2005), (Griffin et al., 2003)
Cyanobacteria	Affect gastrointestinal track, nervous system and skin	0–10	20–35		(Liu, 2006), (Lürling et al., 2013)
Karenia brevis	Respiratory track inflammation	25–45	15–30		(Magaña and Villareal, 2006)

water dependant technologies, such as dry or hybrid cooling systems (Fleischli and Hayat, 2014). In this sense, mitigation of naturalized organisms would include avoiding, as much as possible, water discharges at temperatures optimum for algae growth (Fig. 3).

The salinity over which *Vibrio* bloom is relatively wide, between 5 and 25 ppt, with lower levels in purely fresh or purely ocean water. On the other hand, the optimum salinity range for cyanobacteria is towards the fresh and brackish water range (0–10 ppt) whereas for *Karenia brevis* is in the more saline range (25–45 ppt), suggesting that the distribution of these algal types will vary depending upon the distribution of freshwater inputs and dilution available along the coasts. Climate change may increase the variation of salinity gradients along the coast (Deeb, 2013; Havens, 2015). During the periods of heavy rain and high river flows the salinity of estuarine and coastal environments could drop, expanding the area of low to moderate salinity towards the coast (Havens, 2015). During drought periods, with the combination of sea level rise (salt water intrusion), the salinity of estuarine environments could rise, expanding the area of high to moderate salinity towards the land (Deeb, 2013). Both scenarios could promote the development of new optimal environments for *Vibrio* and harmful algae, increasing public health risk by expanding the geographical range. One potential means of controlling salinity is through the use of gates and other surface water control structures which can shorten salinity gradients in areas where populations are more likely to be exposed.

In addition to temperature and salinity, nutrient levels are also linked to *Vibrio* concentrations and have a major impact on algae blooms. Primary sources of nutrient inputs include agricultural runoff, urban storm water, and wastewater (Fig. 3). These sources are frequently contaminated with animal fecal waste and fertilizers both of which have high levels of nitrogen and phosphorus which are then washed to receiving waters after rain events or from leaking sewers. Therefore, the aim should be multifaceted, reducing the volume of storm water (Livingston and McCarron, 1992) and sewage that is disposed in water bodies, and also reducing its nutrient load by minimizing fertilizer use (Kirkpatrick et al., 2014) and cleaning up of animal waste. In the case of *Vibrio,* they are commonly found in association with plankton (Turner et al., 2009; Lipp et al., 2003), in particular copepods (Lizárraga-Partida et al., 2009). In fact, the *V. cholera* pandemic of the early 1990's was attributed to an upwelling event that brought nutrient rich deep ocean waters to the surface, resulting in plankton blooms and subsequent cholera outbreaks that crossed the continent of South America (Gil et al., 2004). Thus, controlling anthropogenic sources of nutrients which are commonly found along coastal areas, should be considered as part of the strategic approach to minimizing the potential for *Vibrio* infections and the incidence of algae blooms. Furthermore, some of the methods described previously to avoid standing water could be beneficial to efforts to minimize the propagation of algae blooms, since they generally flourish in nutrient rich calm waters, especially cyanobacteria (FDOH, 2017) (Fig. 3). Similarly, blooms of *K. brevis* have been associated with water circulation features along the West Florida Shelf (Maze et al., 2015) and with nutrients (Olascoaga et al., 2008). The impacts of nutrients, however, are complex. For example, Weisberg et al. (2014) emphasizes ecological dynamics which may result in other algae species outcompeting *K. brevis*, depending upon the level of nutrients. Algae are also susceptible to other environmental factors which might be more difficult to control and could encourage algal blooms, such as solar irradiance. Higher irradiance is associated with higher growth rates (Magaña and Villareal, 2006) and it is unclear how climate change will influence the radiant energy reaching different regions of the Earth.

Along with monitoring and controlling environmental factors that affect the growth of naturalized organisms, attention should be paid to additional routes of exposure, which include consumption of contaminated shellfish. This would apply for waters with high concentrations of *Vibrio* or other pathogens. Thus, it is also necessary to improve the shellfish decontamination technologies. In fact, most of the positive cases of *Vibrio* spp infections in the United States are caused by consumption of contaminated raw shellfish (Horseman and Surani, 2011). Traditional post-harvest procedures (PHP), such as: thermal treatment, gamma irradiation, freezing, and high-hydrostatic-pressure treatments, are effective in eliminating the bacteria. However, they often result in oyster death and reduction of its quality (changes in odor, color and texture) (Fang et al., 2015). Novel procedures including chitosan microparticles (Fang et al., 2015), UV disinfection (Ramos et al., 2012) and high salinity shock treatment (Larsen et al., 2013), represent promising alternatives to decontaminate live oysters without affecting their

quality.

Considering the increasing trend of *Vibrio* infection cases and harmful algae blooms, and the difficulty to control their populations in their natural environment, it is important to educate the general population about the risk of infection, to prevent unnecessary contact with *Vibrio* and toxic algae, and to interrupt the transmission route (Fig. 3). This becomes more relevant if areas flooded by sea level rise would be used for recreational purposes. Educational campaigns should include the following information/enforcements: avoid eating raw shellfish from high risk areas (e.g., with ideal temperature and salinity for *Vibrio* bacteria and/or with active toxic algae blooms), avoid entering recreational waters with open wounds (lacerations, puncture wounds and scratches) to avoid exposure to skin pathogens such as *Vibrio vulnificus*, maintain good hygiene and rinse with treated freshwater after seawater or brackish immersion, use protective gloves while manipulating raw shellfish, use protective shoes to avoid cuts at the beach, signage to avoid recreational activities in waters with active algae blooms, avoid use of water with active algae blooms for irrigation without treatment, and avoidance of the coast during active blooms to prevent skin, eye and respiratory irritation from contact and inhalation of aerosolized seawater.

4.3. Mitigation of fecal-oral diseases

As in the case of mosquitoborne disease and diseases from naturalized microbes, sea level rise could have a direct impact on the transmission of fecal-oral diseases, particularly by modifying the environmental conditions that favor pathogen proliferation and increasing the exposure to these pathogens. In addition to *Vibrio* there are other pathogens that can be transmitted through seawater. These additional pathogens usually come from humans or animals and can be transmitted to water through bather shedding (Elmir et al., 2009), direct fecal sources on the beach (Wright et al., 2011), from poorly treated storm water (Sinigalliano et al., 2007), and from leaks in the sanitary sewer system (Solo-Gabriele et al., 2011; Trtanj et al., 2016). Once in the water they can impact coastal sediments which tend to retain pathogens (Mueller-Spitz et al., 2010) and release them through tidal and wave action (Feng et al., 2013; Phillips et al., 2014) (Fig. 4).

A vast majority of these additional pathogens are transmitted through the ingestion of contaminated water, but a few can be transmitted through inhalation (*Legionella*) and skin contact in particular through open wounds (*S. aureus*) (Plano et al., 2013). Moreover, changes in temperature could also be related to higher risks of infection, pathogens such as *Legionella* sp and *Campylobacter jejuni* thrive in particularly warm waters (up to 42 and 45 °C) making them of concern as temperatures rise. Other pathogens such as *Cryptosporidium*, *Shigella*, and *E. coli* O157:H7 also thrive under high temperature conditions (up to 37 °C) (Table 2).

Most of these pathogens have traditionally not been considered to be part of the natural background of coastal ocean conditions; however, an overwhelming number of research studies have shown that even fecal-oral pathogens can become naturalized and persist for long periods of time in beach sands found in the intertidal zone (Whitman et al., 2014; Solo-Gabriele et al., 2016). These beach sands tend to accumulate microbes with the highest levels found just above the high tide line (Shah et al., 2011) thereby serving as a reservoir of potentially infectious pathogens (lower part of Fig. 4). With the increase in sea level, the extent of the intertidal zone will increase as Florida tends to be very flat along its coast resulting in a larger coastal area impacted by tidal fluctuations. This anticipated increase in the intertidal fluctuations can serve to promote greater proliferation of microbes.

To control pathogens along the coast, the sources of fecal contaminants would need to be minimized. This would require hardening and sealing of older sewer systems which often have significant amounts of infiltration and exfiltration. It would also require the redesign of domestic sewer collection systems which in many parts of Florida rely on gravity flow. With increasing groundwater levels, there will be less elevation through which water can flow by gravity and many of the sewer systems along the coast may need to be converted to force mains. Sewage treatment plants, with processes running by gravity, may also need to be redesigned to account for the higher water levels. Sewage effluents from treatment plants (usually secondary effluents) should be

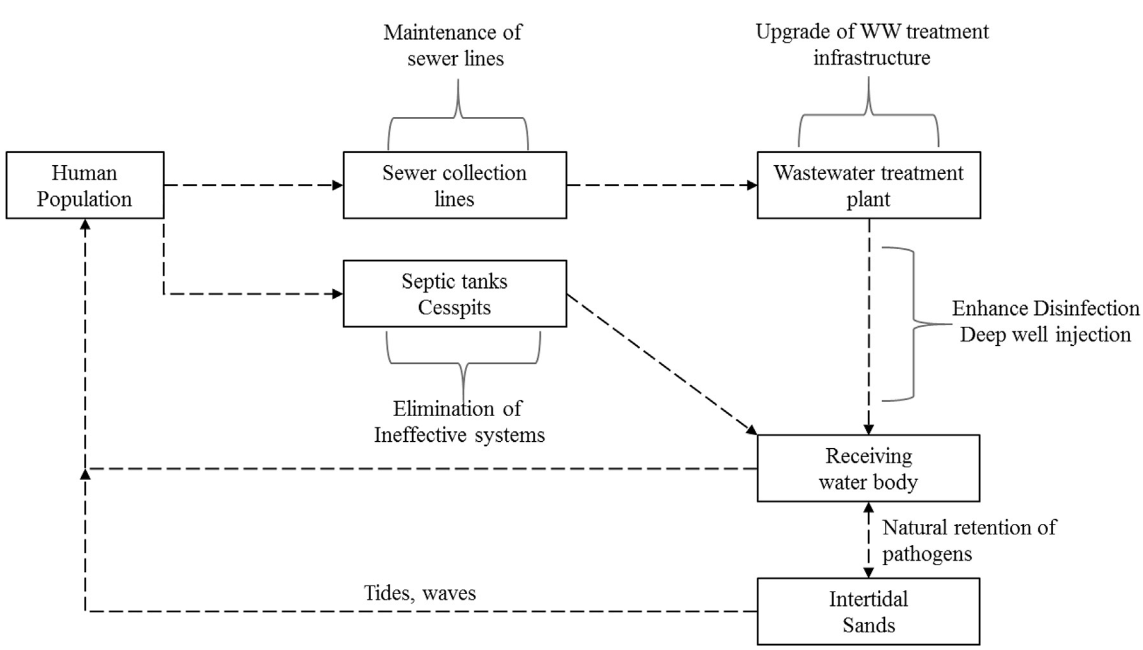

Fig. 4. Mitigation of fecal-oral diseases in coastal zones.

directed away from coastal areas. Even if treated to secondary standards (treated through at least sedimentation and aerobic biological processes), sewage effluent still harbors pathogens (Johnson et al., 1997; McLellan et al., 2015) and nutrients; the pathogens posing a direct infectious risk whereas the nutrients are indirect through their impacts on *Vibrio* and harmful algae. Alternatives to coastal outfalls include deep well injection and reuse of effluent. In addition, the use of advanced treatment such as to a tertiary level (targets nutrient removal), reduces the potential for the spread of pathogens and nutrients. Septic tank systems which rely on gravity should be replaced with sewer networks once water levels impact their corresponding drain fields (Cooper et al., 2016).

Storm water is a known source of fecal bacteria (Hernandez et al., 2014; Patz et al., 2008) and efforts will be needed to treat storm water prior to discharge to coastal waters to prevent human exposures to fecal-oral pathogens. Storm water treatment systems include initial retention of the first flush, infiltration systems, vortex separation systems, and water quality baffle boxes (CH_2M Hill Inc. 2012) along with extended detention and controlled discharge of higher level runoff. With increases in water levels, storage volumes of storm water will decrease within underground and above ground reservoirs. As such storm water systems will need to be redesigned such that the storage volume which treats the first flush is maintained prior to discharge.

Human and animal densities in various areas would also need to be considered to assess the ability of the water to dilute microbes from bather shedding (Elmir et al., 2009) and fecal inputs (Wright et al., 2009). For fecal inputs from domesticated animals, policies can be put in place requiring that owners properly dispose of fecal waste (Kelly et al., 2018). For wild animals, coastal management systems can be put in place that would minimize the excessive congregation of certain types of animals (e.g., vegetated dune structures tend to deter the congregation of birds). Additional transmission routes also include consumption of shellfish harvested from contaminated waters. In this case, post-harvest decontamination procedures also play an important role in efforts to minimize cases of infection.

5. Case of study: City of Key West

The City of Key West is a 14.5 square kilometer island, with an estimated population of 26,990 people (US Census Bureau, 2017). The Florida Keys, located off the southern coast of Florida, are an archipelago with Key West at its southernmost point (Fig. 5). The island receives over three million tourists annually. The United States Navy established a naval base on Key West in 1822. The Naval Air Station, located within 1.6 km of Key West on Boca Chica Key, was established in 1940. The island of Key West boasts a population density of 1703 persons per square kilometer (whereas the rest of the state of Florida has an average of 135 persons per square kilometer) and receives more than 100 times the number of tourists than it has residents.

Key West is a limestone island which allows water to not only flood by overland flow, but also to well up from the ground (Spanger-Siegfried et al., 2014). Seawalls, an effective flood-prevention method in many areas of the world, are inadequate by themselves in preventing tidal inundation due to the island's porous geology (Spanger-Siegfried et al., 2014). While flooding on Key West was previously limited to storm surge events, storm drains are now known to back up and overflow onto the streets during the full and new moon; the City could experience 200 tidal floods annually by the year 2045 (Spanger-Siegfried et al., 2014). Today, even very small amounts of precipitation (on the order of 25 mm), along with extreme tidal events, can cause the island to flood (Spanger-Siegfried et al., 2014). Even though the flooding tends to be shallow, for the time being, this can affect roads and other infrastructure, and cause damage to residences and businesses.

Key West has taken several measures to minimize coastal contamination and prevent flood damage. The city has also eliminated 99.9% of septic tanks and cesspits, reducing the risk of waterborne pathogen spreading in a flooding scenario (CDM, 2001; Monroe County, 2007). Since 1989 the city installed a centralized collection sewer system that conveys (via pumping) wastewater to a treatment facility. Efforts during this upgrade included the detection and elimination of leaks from public and private sewer pipes, and the reduction of seawater intrusion to the system and the reduction of exfiltration which would contribute towards the contamination of groundwater. Since the year 2000, the treated wastewater has been disposed by a deep well injection system.

To address flooding, Key West has developed strict building standards and improved its storm water infrastructure. One of the first integrated floodplain management plans was prepared by the city of Key West in 1971, in cooperation with the National Flood Insurance Program (NFIP), administered by the Federal Emergency Management Agency (FEMA) (Monroe County, 2007). This plan established construction standards for the island and mapped special flood hazard areas. The plan, in conjunction with enhanced building codes, established specific building requirements for these areas. Most important of these requirements being the minimum elevation of new construction. The City of Key West established a minimum finish floor elevation of 30 cm for the whole city and an addition of 0.5 m freeboard elevation within type A flood zones, which are zones where a static rise in water levels can be expected during flood events. The City also passed legislation that allows building heights to exceed the zoning requirements by an amount equal to the provided freeboard of a structure up to 1.22 m, which acts as an incentive to promote building resilience and lowers the potential for those structures to be damaged while reducing flood insurance premiums (Reed et al., 2013).

The latest storm water management plan for Key West included the development of a hydrologic and hydraulic computer simulation model of the City to identify flood prone areas and facilitate the implementation of future adaptation strategies to manage storm water and mitigate flooding. The plan proposes 37 specific projects, with the aim of reducing flooding, decreasing the amount of storm water that is discharged to coastal waters and improving water quality (CH_2M Hill, 2012). The projects include: installation of new gravity recharge wells (especially in the higher elevation areas), installation of new piping to improve collection in some areas, installation of pump-assisted storm water recharge wells in low lying critical areas, retrofitting existing outfalls with baffle boxes to reduce sediments and sediment-associated nutrients, and new infiltration control facilities where possible (exfiltration trenches), among other plans. Given the City's policy of improving water quality and reducing contaminant load to coastal waters, the construction of new outfalls is discouraged. However, in some cases, were the elevation is too low the construction of outfalls may be the only feasible option to remove standing water. It was estimated that the implementation of these recommended projects will divert more water into the ground (which is an acceptable practice since there is no potable groundwater source on the island); 51% in comparison with 45% that is currently diverted with the existing storm water infrastructure (CH_2M Hill, 2012). The City of Key West is also implementing a low impact development or green infrastructure approach to improve storm water quality, including the removal of nutrients.

All of the aforementioned measures have already managed to improve water quality (reduced amount of nutrients and reduced contamination with urban sewage bacteria). In fact, the Monroe

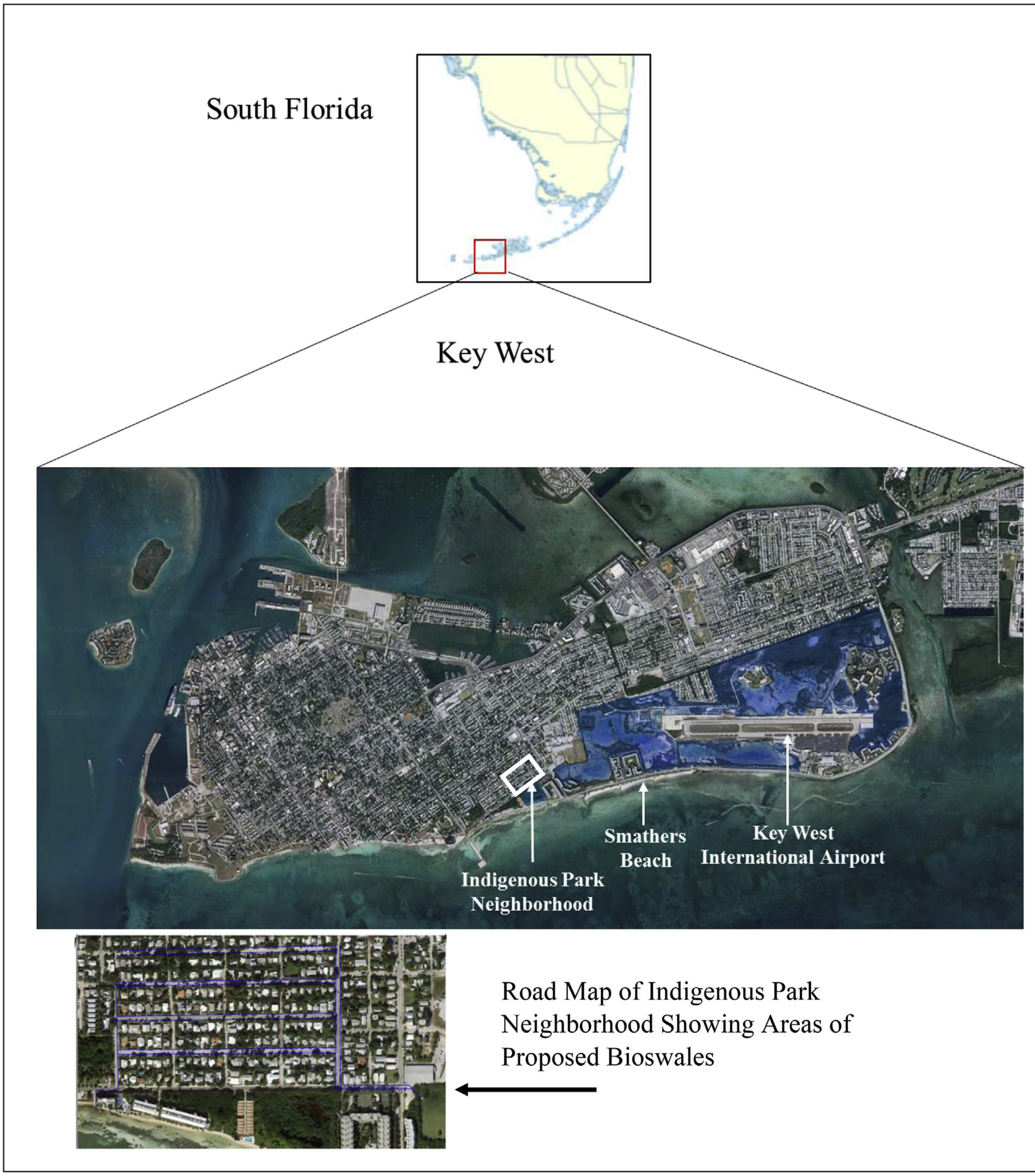

Fig. 5. Location of the City of Key West with an emphasis on the low lying areas of the Key West International Airport and Smathers Beach, and Indigenous Park Neighborhood.

County Canal Management Master Plan Phase I reported that in 3 years of operation of the wells, tests found a 77.8% decrease in fecal coliforms in the City's canal. The current practices of water management at Key West mitigates some of the health risks associated with heavy storms and floods. However, additional mitigation is needed to address areas that suffer from more frequent flooding.

The areas within the City of Key West that are believed to be most vulnerable to sea level rise are: Key West International Airport, Smathers Beach, and the Indigenous Park Neighborhood (Fig. 5). These sites are the most low-lying within the island and represent key economic drivers for the City due to the provision of housing to local residents and their role in attracting and transporting tourists to the island. For the purpose of this paper, engineering solutions for these areas that are already being developed are reviewed, with a particular focus on solutions identified through the Florida Resilient Redesign II (FRRII) Workshop. This was a design collaboration of the Florida Climate Institute, with the specific engagement of local governments, Universities (Florida Atlantic University, Florida International University and the University of Miami), and additional stakeholders.

Key West International Airport (EYW) serves 362,000 passengers annually. Fifty percent of its runway will be flooded with only one-third meter of sea level rise. Due to the lack of available space in this and other nearby islands, the FRRII proposes a mixed use of

the Boca Chica Naval Air Station, for civilian and military airline access. An alternative solution would be to elevate the EYW airport. Similar projects have been executed elsewhere in Florida, for example the city of Miami Beach is undertaking a major effort where entire roads are being raised by 60–90 cm (DK &P, 2016).

Smathers Beach continuously suffers beach erosion from wave energy during storms and from runoff resulting from heavy rain and require continuous sand replenishment. Unfortunately, this practice will eventually become unviable in the future with the sea level rise scenario. Therefore, the suggestion is to allow water to inundate the coastline, where applicable, and reconnect the Atlantic Ocean to the salt ponds behind the beaches facilitating the flow of water to and from the ponds (Fig. 5). This will result in the permanent wash-down of some beaches and potentially their eventual disappearance.

There are several advantages to this approach. It will create a natural buffer zone to the island against storms, it could also allow the increase of biodiversity in the area and it could also create new recreational areas. However, it would also implicate the relocation of highway A1A, increasing the traffic inside the City and the possible accumulation of standing water in these ponds. A practical solution to the later problem would be to increase the depth in areas that are constantly flooding, allowing a greater flow of water from the ocean preventing stagnation. In addition, the removed soil could be used to elevate residences and streets. The addition of pumps to promote water movement is also a possibility; this will serve to aerate the water and maintain a constant flow.

The Indigenous Park neighborhood holds the City's heaviest concentration of flood damaged (repetitive loss) properties and is a critical residential neighborhood in Key West, as it houses much of the City's workforce. As a solution for this region the FRRII proposes to reduce the width of the streets and create a bio swale along them for storm water conveyance and treatment (Fig. 6). The soil removed to create this bio swale could then be used to elevate streets and other infrastructure in the City. In some cases, underutilized roadways, not required for residential access, could be converted to greenways or linear parks that serve many functions and provide multiple benefits including recreational, aesthetic, storm water drainage, and wildlife habitat. This design would provide storm water conveyance and treatment (including nutrient uptake), which improves the performance of the storm water management system. In addition, houses could be raised and integrate rooftop rainwater cistern collection systems. The cisterns could contribute not only to storm water management, by capturing water, but they could also reduce the City's carbon footprint and resource consumption, with the reuse of captured rain water, reducing the potable water demand and associated pumping from the Florida mainland.

Coastal areas of the City intended to be protected in place may require further shoreline enhancements including the use of wave energy dissipaters. While sea walls are one of the most common methods to prevent coastal erosion, the use of conventional fixed walls creates a static structure that does not respond well to undermining and is not easily adapted to future conditions. The use of living sea walls and adaptable structures offers an improved solution over conventional walls by incorporating living systems and rip rap which are both more adaptive than a fixed structure, providing enhanced levels of protection in changing conditions. Innovative wall design also offers an added benefit such as the concaved/curved design which dissipates wave energy rather than reflecting it like vertical walls. The use of living shorelines, reefs and breakwaters also significantly reduce wave energy offering additional shoreline protection from erosion. The various strategies would be studied to ensure appropriate design and placement to mitigate the adverse effects of wave energy along coastlines. Through these strategies, the impacts to natural ecology, water resources and potential for increased vectors can be managed to acceptable levels.

One of the biggest concerns when facing sea level rise, as discussed previously, is the possible health impact and propagation of diseases that could be related to the expansion of shallow water covered areas; therefore, adaptation and resilience are crucial (Ebi and Semenza, 2008; Ebi et al., 2013). On this matter, Key West has already made progress, as the City is currently applying some of the techniques proposed to control disease transmission.

In the case of arboviral diseases, the City executes an integrated approach to control mosquito populations. The Florida Keys Mosquito Control District employs Bti as biological larvicide, the application is executed by air or ground, depending on the size of the mosquito reproduction sites (FKMCD, 2017). In addition, the Florida Keys Mosquito Control District is also responsible for the execution of the adult mosquito control program in the area, which is focused on targeting females (blood feeders). Spraying is executed from the ground with trucks or by air with helicopters, depending on the extension of the affected area (FKMCD, 2017). Furthermore, the Florida Keys Mosquito Control District in association with Oxitec are currently evaluating the application of genetic engineering to reduce the *Aedes aegypti* vector. In this case, genetically modified male mosquitos would be introduced that would pass genes that would cause the death of their offspring (Oxitec, 2016). However, there is strong opposition among residents who are questioning the success of the trials in Brazil (FKEC, 2017).

For naturalized and fecal-oral microbes the enhancements made by Key West to the sewer collection system, the new wastewater treatment plant, the elimination of point sources of contamination (septic tanks) and the deep-well injection system, have already proven to improve water quality in the area. This represents an important factor in controlling the transmission of fecal-oral and waterborne diseases as well as the incidence of toxic algal blooms, since it reduces the occurrence of ideal conditions for their propagation (specifically nutrient and sediment load). However, due to the increase of sea water volume that needs to be managed, it is important to maintain optimal conditions of the collection systems and to upgrade the infrastructure as required in a timely manner. In addition, to control *Vibrio* infections the City should consider the development of a surveillance system that could predict the behavior and incidence of the bacteria as a function of environmental conditions (temperature, salinity, sediments and nutrients) (Mott et al., 2008). In this respect, the State already notifies the public about the occurrence of positive infection cases and deaths related to *Vibrio vulnificus* by County, with data ranging back to 2008. This information is available in the Florida Department of Health (FDOH) website, along with basic information about the bacteria and prevention recommendations.

Aside from sewer disposal, other important nutrient inputs that should be considered are storm water runoff. In fact, storm water runoff is considered one of the major sources of pollution in the state of Florida, given its high water volumes and the amount of pollutants it can carry. Therefore, the aim should be to reduce the amount of storm water that is disposed in water bodies, as well as improve its quality (Livingston and McCarron, 1992). Reduction of the quantity can be achieved through reuse projects which store storm water on site for later uses. Improvement in water quality can be achieved through upstream water management to minimize contaminant sources, retention of the first flush of water captured such as through rain gardens and green roofs, and additional treatment technologies such as vortex flow sediment capture systems and UV disinfection.

The FRRII has already considered measures that would reduce the impact of storm water runoff. One of the objectives of the plan

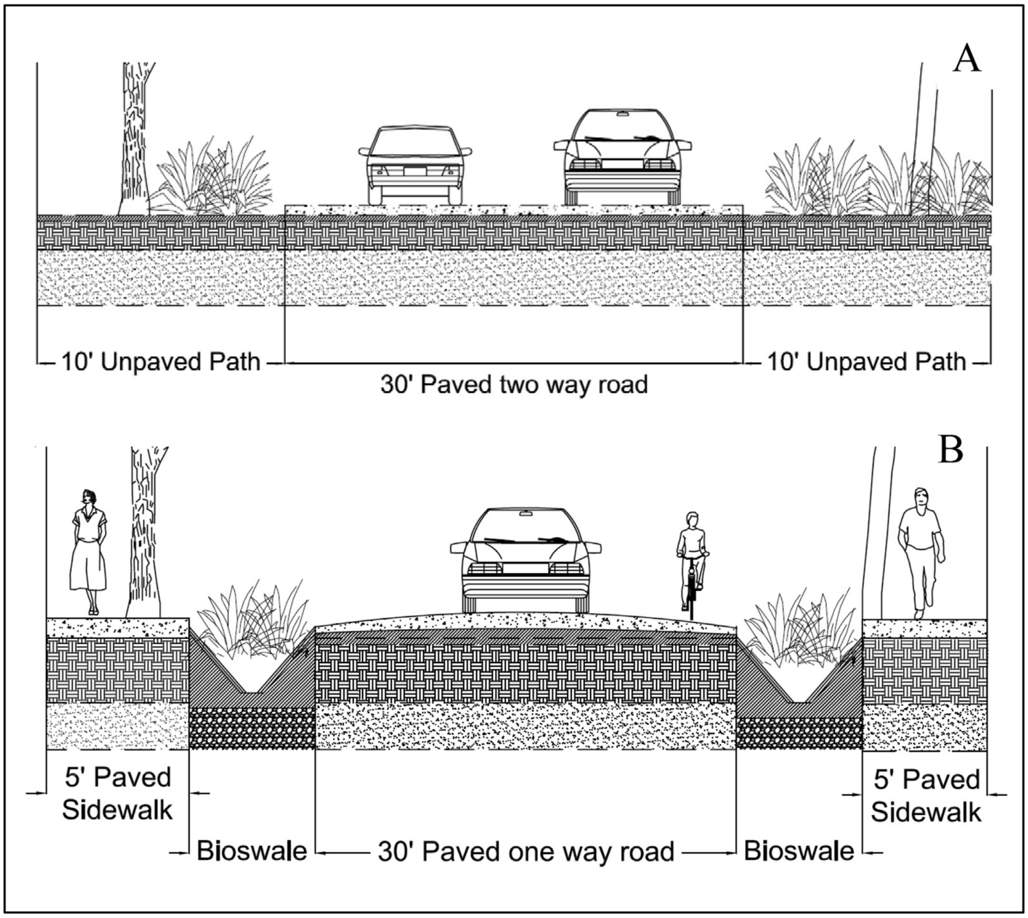

Fig. 6. FRRII Solution to Indigenous Park Neighborhood streets. A. Current layout. B. Proposed bioswale.

entails balanced water use and reuse, including rainwater catchment (collecting cisterns) and storm water management through low impact design that promotes treatment and reuse. In addition, the City could implement a policy that encourages the population to reduce the use of fertilizers, minimizing the content of nutrients in storm water runoff. As part of the resilient redesign, not only reuse of water should be considered, recovery and reuse of nutrients from wastewater and storm water runoff should be added as part of the objectives, to minimize environmental impact and improve sustainability. Several technologies are being studied to improve the rate of nutrient recovery from wastewater, some of these are: struvite precipitation, adsorption treatments (ion exchange processes), electrochemical precipitation and electrodialysis (Batstone et al., 2015; Puchongkawarin et al., 2015; Franco et al., 2017).

6. Conclusions

Sea level rise is inevitable and with it, associated changes in the extent of disease transmission pathways. The intrusion of seawater and the expansion of shallow water covered areas pose an ideal scenario for the creation of new mosquito breeding sites. Similarly, the geographical expansion of shallow covered areas and the increase in water temperature present ideal conditions for the propagation of waterborne pathogens (specially *Vibrio* spp) and toxic algae blooms, exposing new populations to these health risks. The transmission of fecal oral diseases could also be affected since sewer collection lines will become more vulnerable to flooding and salt water intrusion, increasing potential exposure to these pathogens.

Given that greenhouse gas emissions are likely to continue, with the consequent increment in average global temperature and sea level, adaptation will be required. Here we propose some adaptation strategies focused on methods to minimize or control disease transmission due to sea level rise. Arboviral diseases can be controlled by the application of an integrated approach that targets mosquito's life cycle at its different stages, with control measures consisting of mechanical, biological and chemical methods. Consideration will be needed to account for changes in salinity patterns, due to salt water intrusion, which at the current time greatly influences mosquito proliferation (mosquito species of interest require < 25 salinity units to reproduce).

The spread of naturalized microbes, such as *Vibrio* and toxic algae, can be greatly reduced by engineering solutions designed to minimize nutrient (nitrogen and phosphorus) inputs discharged from uncontrolled sewage disposal, storm water, and urban and agricultural runoff. Nutrient recovery technologies should also be considered to improve water quality. Developing a monitoring system based on environmental parameters (salinity, temperature, nutrients, sun light) is also recommended.

Fecal oral pathogens (and *Vibrio*) can be controlled by minimizing liquid discharges that have direct impact on water temperature and salinity. Power plant cooling blowdown is of particular interest due to its high volume and warm temperatures. The development and application of less water dependent cooling technologies should be considered. Most importantly, proper water

and wastewater management is encouraged. This includes the elimination of point sources of contamination (such as sewage effluents), and minimizing non-point sources (such as animals). Efforts are needed to maintain the wastewater infrastructure and its operation should be adapted to withstand higher volumes of salt water. It is also important to reduce the exposure to these pathogens, by the application of novel decontamination processes that allow safe consumption of raw shellfish.

The engineering solutions described previously acknowledge the inevitable flooding in the future caused by sea level rise. Solutions applied to other cities around the world, such as building a wall at the coast, are not feasible due to Key West's permeable karst coral and limestone subsurface geology. As such, innovative solutions are needed to address sea level rise in Florida. Policy changes that incentivize permitting for new sustainable and resilient strategies will be a first requisite to making the needed infrastructure changes a reality. Municipalities, Counties and States will need to collectively and collaboratively adopt approaches that promote these adaptation strategies, as permitting responsibilities fall within these multiple jurisdictions. This will require cross agency integration of policies which can be facilitated by groups such as the Southeast Florida Regional Climate Change Compact.

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